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WIND GENERATING STATIONS UNDER JOINT OPERATIONAL CONDITIONS

A. Kroms

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16. Abstract

Wind power generators in combined operation; review of fundamentals of wind power as energy source and of its characteristics; structural features of generators; feasibility of combined wind power and hydraulic power station; economic outlook for wind power. Bibliography.

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A. Kroms

In order to be able to evaluate the wind energy it is necessary to consider the peculiar features of this type of energy source. Wind generating stations are energy-producing installations with variable available power levels. They can only be successfully exploited when these installations are properly integrated with other systems, as is the case for hydro-electric stations. /135*

1. FUNDAMENTALS OF ENERGY SOURCES

The following questions arise in the discussion of the increasing energy requirement of the Earth:

1. How long will the energy sources known today be available? / 136
2. What is the best possible way of exploiting these energy sources?
3. What new energy sources can we expect to use for energy production in the future?

At the present time, two types of energy sources are being used for energy production, fuels and hydroelectric power.

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* Numbers in the margin indicate pagination of original foreign text.

In many countries, power generation is depended on the availability of fuel. Fuels have a high energy content which favors energy production. The high grade fuels can be easily transported and make it possible to locate the energy production centers at the consumption centers. Technically it is possible to build fuel-driven generating stations with maximum installed power level, and the installation costs per unit of power are relatively low. Thermal power plants can be installed almost anywhere and are available at any time. In other words, they are capable of satisfying all load requirements within their designed power level. Therefore they represent the group of the most adaptable energy production installations.

The fuel-consuming power plants have certain energy and technical advantages. However, they have certain disadvantages which must lead to certain restrictions of construction.

1. The most important fields are gradually being used up, which means that they should be exploited with a great deal of caution.

2. Fuel is not only available for energy production but is also a raw material for the chemical industry.

3. All these sectors of energy users are dependent upon fuel which are only partially served by the centralized energy supply system, for example, traffic, the heating of buildings, heat requirements of industry, etc. This consumes considerable amounts of fuel.

4. The available fuels are distributed in an irregular way so that in many countries there are no fuels at all or there are no large fuel reserves.

5. Considerable amounts of fuel are required continuously in order to operate the thermal generating stations. The mining and transportation of these fuels involves a great deal of effort.

Thermal power plants still operate with large heat losses, and attempts are being made to reduce them. The fuel reserves can only be conserved if other energy sources are used for energy production. The energy sources which are continuously being renewed by natural processes are water energy, wind energy, tide energy, radiation energy of the sun, etc. Up to the present, only hydroelectric power has been used successfully for producing electrical energy. The energy advantages of hydroelectric stations are caused by the fact that the energy carriers flow to the generating station automatically. Therefore, no work is required to move the energy carrier. However, this type of energy production is associated with certain disadvantages:

1. The specific energy yield from each power unit of the energy carriers is relatively small, which means that very large amounts of the energy carriers are required. In this way the installation costs of the generating stations are increased.

2. Generating stations are tied to the availability of energy sources which often means that they must be built a large distance away from the consuming centers. This increases the cost of transmitting the energy.

3. The natural availability of the energy carrier is distributed unevenly, which considerably changes the available power level of these power plants. The available energy supply is a function of the incoming amount of the energy carrier, which is why these power plants are called independent generating stations. In the case of dependent generating stations, for example, hydroelectric stations, it is possible to have a certain

degree of elasticity by storing the energy carrier. However, the storage of large amounts of material with a small specific energy content leads to several restrictions. If these restrictions are not satisfied, then the storage is either connected with very high investment costs or cannot be done at all.

The energy supplied by the dependent generating stations is a function of natural processes. Therefore, they must interact with the independent generating stations, which can be arbitrarily contolled, for example, the thermal generating stations. These stations equalize the power deficiencies of the dependent power plants during certain times of the year. The development of composite systems will therefore be required by the installation of the dependent generating stations.

As mentioned before, the group of dependent generating stations at the present time only contain hydroelectric stations. Even though hydroelectric stations are being built at a fast rate, the energy requirement of the Earth is increasing so fast that 70-80% of the electrical energy must be produced by thermal generating stations. Recently, the role of thermal generating stations has been increased instead of being reduced. Even though hydroelectric stations have not been completely developed, and some possibilities in their development remain, they will not be able to cover the increased energy requirements.

These circumstances have forced the energy industry to look for new methods of energy production. Certain successes can be expected from the technical developments of the exploitation of atomic energy. Even though this method is promising, a certain amount of time will be required to harness atomic energy for energy production. In addition, the energy carriers required for this type of atomic energy production (uranium, thorium) are only available on the Earth's surface in restricted amounts.

Therefore, it is necessary to continue the development of all other types of energy sources.

Wind energy has become more important within the group of new energy sources. Also, tide energy is being studied.

2. CHARACTERISTICS OF WIND ENERGY

Wind energy plays almost no role in present day energy production. This can be explained because of the following reasons:

1. The technical difficulties of building high power wind power generation stations.

2. The fact that the wind force is very irregular, and the fluctuations cannot be controlled.

1. It is basically easy to exploit the wind force. Small wind wheels for local requirements are quite popular. However, this is not the case for maximum performance wind generation stations, which will be used for supplying the public with energy. In this case, the wind energy is inferior to water energy, because

a) Water is an energy carrier with a large energy content because of its much greater specific weight;

b) The water energy can be collected at a point on a river, by damming it and producing a concentrated height variation;

c) The available water energy is more uniform than the available wind energy.

In the case of wind, there are two possibilities of concentrating the energy carriers or storing them. This is why the wind wheel must obtain energy from the free wind flux. The small energy content of the air masses in motion increases the dimensions of the wind wheels, which makes the construction and erection of wind generating stations more difficult.

When wind wheels are constructed and enclosed, the following requirements must be satisfied.

1. The wind wheel must exploit as large a wind segment as possible with a reasonable efficiency.

2. The wind wheel must rotate fast in order to reduce the dimensions and weight of the unit.

3. The wind wheel must be installed high above the ground, because there the wind flux is greater and more uniform. It is important for the wind wheel to have the proper torque characteristics which will make it possible to have stable operation in parallel with an alternating current network. The angle of incidence of the wings must be adjustable so as to exploit the large wind velocities. This is because the high wind velocities bring about the greatest energy yield of the wind generation stations. Aerodynamic knowledge has reduced the number of blades which then increases the specific rotation rate of the wind wheels. In this way one obtains a rapidly moving wind wheel with 2-4 wings. Wind wheels with a diameter of up to 100 meters are required for high performance wind generation stations. It is difficult or maybe even technically impossible to build these. If the electrical generator is installed in the gondola in addition to the wind wheel, it makes up a closed unit. Since for large wind wheels, the rotation rate is limited by the centrifugal forces, it is advantageous

to use a tooth gear between the wind wheel and the generator. The total efficiency of the entire unit is estimated to be η_{cl} = 0.65...0.70 for favorable loading conditions.

The power and energy yield of the wind unit is influenced by the position of the wind wheel with respect to the wind stream. The wind intensity is considerably smaller in layers close to the ground than in the higher air layers. Wind measurements have shown that at altitudes above 150-200 meters, the wind stream is much more uniform than near the ground. Therefore, it is very advantageous to erect the wind generation stations high above the ground. This will result in the following two advantages:

a) The energy yield of the wind generation unit is increased;

b) The difficulty associated with energy production under conditions where the wind velocity changes suddenly will be reduced at the high altitude.

For high power wind generation stations, towers with a height between 100-200 meters will be required. Such towers could be built in principle but such a tower will consume vast amounts of materials and will increase the building costs of the wind generation stations.

Table I gives a number of wind generation units [1]

TABLE I. WIND GENERATION UNITS PRODUCTION SERIES

	Aggregate size	1	2	3	4	5
Diameter of the wind wheel	m	60	80	100	120	130
Tower height	m	100	125	150	175	200
Wind intensity designed for the unit	m/s	12.0	14.0	14.0	15.0	15.5
Power*	kW	1,140	3,150	5,000	8,820	11,800

* At η_{cl} = 0.65.

The production times of the nominal power level and the total power produced per year depends on the wind intensity frequencies, the partial load efficiency of the wind wheel and the design of the generator power, i.e. the level of the wind intensity at which the nominal rating of the generator is reached. The design power level selection has the same effect as in the case of hydroelectric generating stations. The more the generator power is increased for a given wind wheel, the greater will be the energy yield, but the number of hours at which the installed power can be obtained will be reduced. It can be assumed that it will be necessary to exploit wind intensities up to 15-18 m/s for the complete deployment of the wind wheel blades. For even greater wind velocities, the automatic control system will adjust the blades in such a way that the unit will continue to operate at maximum power. The time period over which the wind generation units can be used will be about 2,000 hours per year on the average.

When the performance curves of the wind generation stations P = f(t) are established, it should be realized that the calculation for the condition of changing wind velocity is performed using the so-called cubic formula /138

$$P = k D^2 v^3$$

(P - power, D - wheel diameter, v - wind velocity)

which is erroneous for wind wheels which are coupled with an alternating current generator [2,3,4]. The reason for this is that the cubic relationship applies when the speed ratio remains constant, i.e. for u/v - const. (u circumferential velocity of the wheel). This means that when the wind velocity is increased, the rotation rate of the wind wheel increases in proportion and the wind wheel runs with optimum exploitation of the available wind energy for all wind velocities. In the case of electrical wind generating units, the rotation rate is determined by the line frequency and must remain unchanged for all wind velocities. In the case of wind generating stations, (n = const), it is therefore necessary to determine the power of the wind wheel at any wind velocity from the torque curve $M = \varphi(v)$.

Because of the rapid fluctuations in the wind velocity, several problems must be solved for parallel operation of the wind generating stations and the public line network. The most important problems are the following:

1. A safe automatic system for turning the unit on and off (synchronization) which must often be done when the wind changes.

2. Stable running of the unit (without pendulum motion) even for greatly changing wind velocity.

3. An effective power control which protects the generator against overloads.

In order to direct the wind energy to the line in a simple way, many suggestions have been made such as producing direct current at the wind generation stations. The generating stations would then be connected with the overland line using a rectifier installation. Another method is to use asynchronous generators which operate in parallel with the overland line network and which supplies the timing pulse. However, this can only be done for smaller units.

Research on the applications of wind wheels for driving alternating current generators has shown that it is possible to obtain a stable operation of the wind generating units in conjunction with the alternating current network if the torque characteristic $M = f(n)$ is properly adjusted. However, if rectifier units are nevertheless required in order to have a more elastic coupling between the wind generation station and the network and to thereby avoid the danger of frequency fluctuations when the wind changes, we believe that in the long run this will not be the most important factor. We can expect that in the future the problem of rectification will be solved in a satisfactory way. The question of rectification also occurs when energy is conveyed over large distances from the remote hydroelectric stations. It is expected that this energy transport over large distances will become possible using direct current and more efficient methods. However, there are important technical problems yet to be solved.

Several projects have already been worked out for high performance wind generating stations [1, 5]. At the present time, they cannot be executed because the wind energy problem still requires some technical development and research. It will be useful to build a few test installations with power levels of a few thousand kW. These would then be tested according to a certain program. In spite of a few failures which have been encountered during the exploitation of wind energy, work is progressing in many countries on this topic. The reason for this is the requirement for saving fuel and producing a new means of producing energy. The activities of the British Electricity Authority (BEA) are of particular interest. They have built two test installations with a power level of 100 kW each in order to obtain experience with the joint operation of wind energy generation stations and the British electrical network. The BEA intends to build 50-60 wind generating stations with a power level of 100 kW each, which will be installed on about 80 meter towers. They will be installed at various locations on the British Isles. The first test installations have been built according to the two construction methods given in Figure 1:

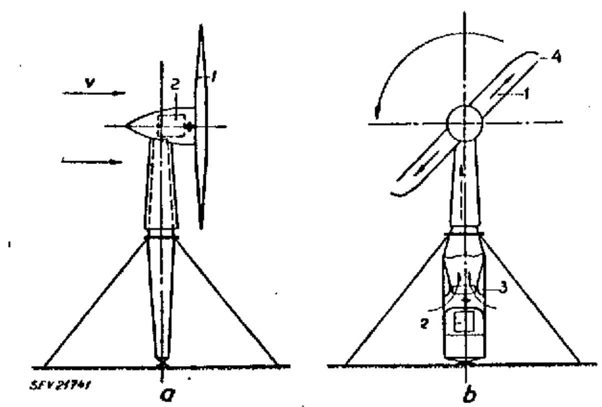

Figure 1. Construction types of wind generating plants.

a- generator on the top of the tower, coupled with the wind wheel; b- generator at the foot of the tower, without direct coupling with the wind wheel; 1- windwheel; 2- generator; 3- wind turbine; 4- air exhaust

a) In the case of the wind wheel shown in Figure 1a, the electrical generator is housed in a gondola having the shape of the streamlines. It is connected with the wheel to a tooth gear. The unit is compact and has a high efficiency, but it is difficult to install a generator on a high tower. A test installation of this type (100 kW) was built by the North of Scotland Hydroelectric Board and is running on the windy Orkney Islands.

b) A wind generation station of another type (also 100 kW), Enfield-Andreau (Figure 1b) construction, has been built in North Wales [6]. This installation is characterized by a peculiar transfer of the wind energy to the generator. The generator is located at the base of the tower and there is no direct connection with the wind wheel. The blades of the wind wheel are hollow and have holes at the tips. The tower is in the form of a support- /139
ing tube, and its interior is connected with the cavity in the blades. When the wind wheel turns, it operates like a centrifugal blower and sucks the air out of the tower. The air running through the holes at the base of the tower drives an air turbine which is directly coupled with the generator. The generator operates like an asynchronous motor, and after this it takes over

the load by operating as a synchronous generator. The installation and control of the electrical generator is much simpler than for the unit shown in Figure 1a. The electrical energy deficiency, on the other hand, can be expected to be much lower than when the generator is directly driven. Also the material costs should be higher.

2. Wind generation stations are typical types of dependent energy units, because their operational power level depends on the wind intensity. The available power of the wind generation stations is less continuous than the power level from hydroelectric stations because the water available changes more slowly. Under favorable conditions, the water can even be stored which makes it possible to adjust the power from hydroelectric stations to the energy requirements more or less. On the other hand, the power output of wind generation stations follows all the changes of wind intensity, and these occur often and are even difficult to predict. The discontinuous and uncertain power generation is the most characteristic feature of wind generating stations. This means that it is impossible to provide a certain electrical requirement with a wind generating station alone.

The situation is similar for river hydroelectric stations (running generating stations). Any river has a certain minimum flow which is available over the entire year and will always provide a certain minimum power level for the generating station. Under high water conditions, the power level is greater than this constant power level, and the high water periods always occur during the same season. At any time, the power level of a wind generating station can drop to zero. This is why certain equalization installations are always required for wind generating stations. The wind energy can only be successfully exploited if it becomes possible to equalize the power drop of the wind generating stations on windless days, using a suitable technical and economic method. Jointly operating systems and their associated vast transmission systems can be used here. The dependent generating stations can best be exploited by coupling them with the networks of the joint system. In this way it is possible to provide power equilization among the generating stations. The hydroelectric stations have requested the development of joint systems. In the future we believe that wind generating stations should also be included in the systems. By parallel operation of the various generating stations, the best overall result of energy production will be produced.

3. THE INTERACTION OF WIND GENERATING STATIONS AND HYDROELECTRIC GENERATING STATIONS

Wind generating stations must be operated in parallel with other generating stations, and the latter will cover the energy deficiencies during zero wind conditions. The equalization power level required in order to replace the wind generated power during wind deficiency periods can be provided by thermal or hydroelectric generating stations. The development of large-scale joint systems will provide favorable conditions for exploiting wind energies. Large networks can absorb the energy offered by the wind generating stations at any time without causing any disturbances. We believe that the joint operation of the wind generating stations and controllable hydroelectric stations is especially attractive. The water reservoirs will be used for equalizing the energy offered.

Any generating station does not only have to provide a certain amount of energy but must also cover a certain power requirement. In other words, it has to develop the required power at certain times, when the power requirement exists. Therefore, it is necessary for the generating stations to satisfy energy balance and power balance requirements at the same time.

Now we can see the difference between the independent and the dependent generating stations. The group of independent generating stations is made up of thermal generating stations and controllable hydroelectric stations, which have storage facilities. These plants can develop their full power output at any time (except for the power which must be provided when they are serviced). The group of dependent generating stations include the hydroelectric generating stations which cannot be controlled or only can be controlled to a limited extent, in addition to thermal generating stations [7]. In the future, this will also include the wind generating stations.

In the case of dependent generating stations, the energy yield is influenced by the yield and operating regime of the energy source. If it is not possible to store the energy carriers, such as is the case for the river generating stations and the wind generating stations, then these generating stations must be used to cover the basic power requirements. In this way the valuable energy source will be exploited as much as is possible. The operational power level of these generating stations P_a will then fluctuate according to the fluctuating energy of their energy sources.

The power balance for joint operation is determined by comparing the yearly curves of maximum power and the curve of operational power of the generating stations (Figure 2). The requirement for independent power P_t is found to be the ordinate difference between the curves $r\,S = f(t)$ and $P_a = \varphi(t)$. The most serious power balance situation occurs during the time periods in which P_a has dropped considerably. The maximum difference

$$P_{tn} = (r\,S - P_a)_{max}$$

is the power which must be installed in the independent generating stations. If the power P_{tn} is increased by the fluctuations of the curve $P_a = \varphi(t)$ we find the installed total power of the joint system to be

$$P_n = P_{an} + P_{tn} > r\,S_0$$

where S_0 is the highest yearly load. In this case the difference /140

$$P_k = P_n - r\,S_0$$

is the equalizing power level which is required to replace the power drop of the dependent generating stations. Since the equalizing power increases the installation costs of the joint system, it is necessary to equalize the curve $P_a = \varphi(t)$ as much as possible so as to reduce the required equalization power.

In the case of wind generating stations, one must reckon with windless days during any season. Therefore, we must set $P_a = 0$ for the wind power in the power balance from which we find $P_{tn} = rS_0$ and $P_k = P_{an}$. This means that the power of the wind generating stations must be double the equalization power level, because at any time the wind generating stations can interrupt their energy production during periods of peak load. On the other hand, for the hydroelectric stations we have $P_k < P_{an}$, especially when their peak operational power can be equalized by water storage. Even day storage facilities make it possible to displace the load area of the hydroelectric generating stations in the load diagram for joint operation, depending on the water supplied by the river (Figure 3). The possible peak power P_h can be influenced by the associated load regime. If there is a water deficiency and if the load zone of the generating station is displaced in the direction of the peak load, then during maximum load period there will be an increased peak power. If the peak power of the hydroelectric station can be maintained in this way over the entire year, then the equalization power is not needed. On the other hand, if the water level is low and it is not possible to avoid a power drop even for peak load

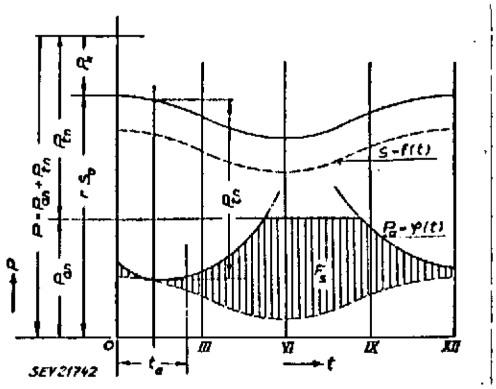

Figure 2. Power balance sheet for systems operating together.

$S = f(t)$ yearly curve of maximum daily loads; r = reserve factor; P_{an} = installed power of the dependent power generating plant; $P_a = \varphi(t)$ curve for the available power of the dependent power generating station; P_{tn} = installed power of the independent power generating station; P_k = equalization power; t_a = period of the maximum power balance sheet; F_S = area of the available power over the season.

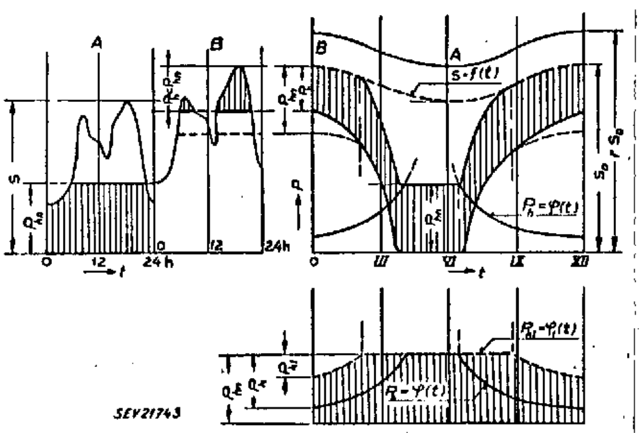

Figure 3. Operational method of controllable hydroelectric stations.

The load zones of the hydroelectric station:
A - for a high water level (basic load)
B - for a low water level (peak load)
P_{hn} = installed power of the hydroelectric stations; P_h = operational range of the peak loads of the hydroelectric stations; $P_h = \varphi(t)$ and $P_{h1} = \varphi_1(t)$ = curves of the available water power with and without flux control; P_k and P_{k1} required initial power levels for basic and peak load operation.

operation ($P_h < P_{hn}$), then the equalization power is required even though it is relatively smaller than for true river generating stations, without any storage facilities.

For joint operation it is advantageous to match the operational regime of the wind generating stations and of the hydroelectric stations. The water reservoirs can be used as energy accumulators and the wind generation stations will in part replace the thermal equalization performance for the hydroelectric generating stations.

During the various seasons the wind generating stations and the other types of generating stations will operate as a joint system as follows:

1. During high water periods, when the hydroelectric stations are loaded to the maximum extent, the thermal generating stations of the joint system are relieved by the wind generating stations. During this period, the wind generating stations only maintain the energy balance of the joint system. During this season, this does not represent a disadvantage because during high water periods, there are usually no deficiencies in power in a joint system.

2. In the case of a low water level when the water reserves have already been partially processed and where the hydroelectric stations operate under peak load conditions, the load regime of the hydroelectric generating stations must be adjusted to the available wind energy (Figure 4). In this case /141
the wind generating stations can be used on windy days to replace the hydroelectric stations, so that the water reserve can be conserved. In the case of strong winds, the wind generating stations run under a full load and cover the basic load. The contribution of the hydroelectric stations to the power and energy balance of

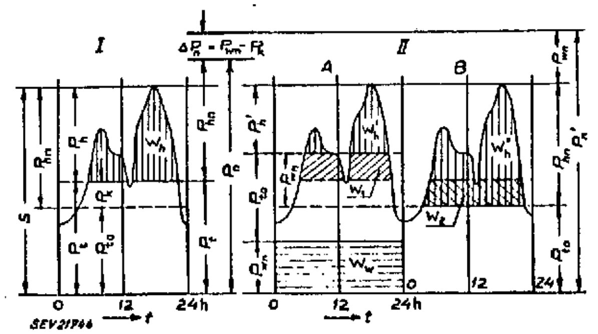

Figure 4. Interaction of the wind generating stations and the hydroelectric stations.

I - Power balance sheet without wind generation stations (for low water level).
II- Power level with wind generating station;

A- on windy days
B- on windless days

P_{wn} installed power of the wind generating stations: P_t and P_{to} installed power of the independent generating stations (for r = 1.0); $1'_k = P_t - P_{to}$-output performance; $\Delta 1'_n = P_{wn} - P_k$ -increase of the installed overall power after inclusion of the wind generating stations; W_h and W_w- energy yield of the hydroelectric stations and the wind generating stations; W_1- level of the water reservoirs on windy days; W_2- processing of the stored water reserve on windless days.

the joint system can be reduced. The hydroelectric stations decrease their water reserves in the storage areas during this time. During the subsequent period of no wind, the hydroelectric stations process the stored water reserves and can therefore achieve an increase peak performance. If it is possible to equalize the peak loads of all the dependent generating stations $P_n = \varphi(t)$ by an interaction of this type, then the wind generating stations will perform the function of the equalization power generation. In other words they replace the thermal compensation power P_k. This means that the installed total power for joint operation is only increased by a factor of $\Delta P_n = P_{wn} - P_k$. The ratio $\gamma = P_k/P_{wn}$ is the coefficient of the guaranteed power. When thermal generating stations are used, we have $\gamma = 0$. On the other hand, if the reserves of the hydroelectric stations are used in order to bridge the power deficiencies of the wind generating stations, then we may have $\gamma = 0.2...0.3$ which means that it is possible for 20-30% of the installed wind generating power to be included in the overall power generator.

Figure 5 gives diagrams of the total power with and without the wind generating stations. In the first case the power reduction of the hydroelectric stations must be equalized by an additional thermal power generation P_k. After the wind generating stations are set into operation, a reduced thermal power P_{t0} is sufficient for joint operation, because all of the dependent generating stations can cover an increased power requirement. On windy days this is done by the wind generating stations and on windless days it is done by controllable hydroelectric stations which develop an increased peak power because of additional stored water. In this way the dependent generating stations cover an increased power $P_a = P_{hn}$ of the total power, which means that the power of the thermal generating stations can be reduced by a factor of $P_t - P_{t0} = P_k \cdot$

The expect coefficient of guaranteed wind generator power $\gamma = P_k / P_{wn}$ must be determined based on load and power curves. Approximate reference points for γ can be calculated using the following simplified relationships.

We have

W_1 (kWh/day)	The energy stored during windy days;
W_2 (kWh/day)	Energy which is produced by processing the stored water reserves;
T (h/year)	The amount of hours the wind generating stations are used.

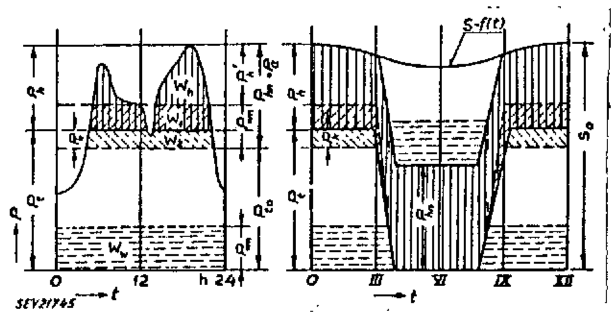

Figure 5. Diagram of the load distribution for joint operation with wind generating stations. Notation as in Figure 4.

In order to simplify the problem we will assume that the windy days are equally distributed over the entire year and that the W_1 and the W_2 values do not change during low water level periods. This means that the energy balance between the wind generating stations and the hydroelectric stations can be expressed as follows:

$$\frac{W_2}{W_1} = \frac{T}{8760 - T}$$

or

$$W_1 T = W_2 (8760 - T)$$

According to Figure 5

$$W_1 = (P_{wn} - P_k)\, t_1$$

and

$$W_2 = P_k\, t_2$$

where t_1 and t_2 (h/day) are the durations during which the generating stations are used in the corresponding load zones of the total load diagram.

After substitution of these W_1 and W_2 values we find

$$(P_{wn} - P_k)\, t_1\, T = P_k\, t_2\, (8760 - T)$$

from which it follows

$$P_{wn} = P_k \frac{(8760 - T)\, t_2 + T\, t_1}{T\, t_1} = P_k \frac{(8760 - T)\, k + T}{T}$$

(where $k = t_2/t_1$)

At k - 1.0 from this we find

$$P_{wn} = P_k \frac{8760}{T} \text{ and } \gamma = \frac{P_k}{P_{wn}} = \frac{T}{8760}$$

In practice we have k > 1.0 and the k values depend on the type of load diagram and the working capacity of the hydroelectric and wind generating stations. Using these approximate relationships we can achieve the following values for the wind power:

			$T = 2000$	2500 h/year
at	$k = 1.0$	$\gamma =$	0.23	0.29
	$k = 1.2$	$\gamma =$	0.20	0.26

These numerical values can be achieved with moderate water reserves which are sufficient for storing the required water over a period of no wind. Even weekly storage units can be used for this. We may even expect a greater gain if we consider the fact that during the dry years the wind generating stations can also be used to fill the water reserves during the high water periods. In this way the fluctuations of the available water power can be reduced during various hydrological years.

This means that a coupling of both types of dependent generating stations, the wind generating stations and the hydroelectric stations results in a joint operation with an energy production method which has greater elasticity than if both types of generating stations were used independently. By unloading /142 the hydroelectric stations during windy days the water reserves are correspondingly increased which sometimes justifies an increased installed hydroelectric power level. This makes the hydroelectric generating stations contribute more to the overall power of the joint system and results in a better exploitation of the water flow. The wind generating stations can be used as energy producers for controllable consumers because the energy to these consumers can be generated during times when the hydroelectric stations do not require any equalized power [8].

Because of the development of large-scale networks, the assumptions for exploiting wind energy are favored even more. For joint operation over a wide area, it is possible to build individual groups of wind generating stations at various windy locations, which are separated by large distances from each other. In this way we may expect that at any time at least part of the wind generating stations will be operating and the total energy offered of the wind generating stations will be more uniform. In this way the participation of the wind generation station complex in the overall power generation of the joint system will be improved.

4. ECONOMIC EXPECTATIONS FOR WIND GENERATING STATIONS

The influence of wind generating stations to the total energy and power of joint operation can be expressed in the following way:

1. The total energy is improved by using wind energy, because the fraction of thermal generating stations and correspondingly the fuel consumption is reduced.

2. The total power is reduced, on the other hand, because the wind generating stations require an equalization power.

The fuel savings which can be brought about by exploiting wind energy must be related to the increased installation costs associated with the power level increase and the higher specific building costs of the wind generating station. The characteristics of the wind generating stations must not be compared with the average characteristic values for joint operation, but instead must be compared with the characteristics of certain generating stations, the so-called replacement generation stations [9]. The replacement generating stations are those stations which would have to increase their power and energy yield in order to cover the increased energy requirement, for the case where the planned generating stations, the wind generating stations, are not built. Wind generation stations must therefore be compared with thermal generating stations because they will replace only thermal generating stations for joint operation conditions. The development of hydroelectric generation stations should not be delayed in any way because wind generation stations are being built.

In any economic comparison, it is necessary to use the output numbers which are the result of using the corresponding installations for the same working conditions. Therefore, it is first necessary to determine the energy characteristics which are required for meeting the given energy requirements. It is necessary to consider the power increase when establishing equivalent energy characteristics which are produced by the fluctuations of the operational power level of the dependent generation stations. Only under these conditions it is then possible to make a direct comparison of the building costs of the generating stations, if the generation stations do not require any equalization power, i.e., when the installed power level is completely exploited for the total power level. If this condition is not satisfied, than the building costs must be corrected by the guaranteed power/ coefficient $\gamma = P_a/P_{an}$ where P_a is the available power of the generating station during the period of maximum total power requirement over the year. In addition, it is necessary to consider the various costs and energy losses of the energy distribution networks.

The most important economic criterion, the energy costs, is expressed approximately as follows:

$$s = \frac{pk}{t_n} + f \qquad (\$/\mathrm{kWh})$$

where k (\$/kW) The specific building costs.

p The yearly fixed expenditures.

f(\$/kWh) The costs which depend on energy production, primarily consisting of the fuel costs.

t_n(h/y) The exploitation hours of the installed power.

If the coefficient of guaranteed power is $\gamma = P_a/P_{an} < 1.0$ for the dependent generation station, then each MW of power installed in this generation station can only replace γ(MW) in the replacement generation station. Therefore, the fixed yearly costs $p_1 k_1$ (\$/kW/year) of the corresponding generation station must be compared with the savings $\gamma k_2 p_2$ in the replacement generation station. This means that the equivalent energy costs for the same level of guaranteed power is expressed as follows:

$$\frac{p_1 k_1}{t_n} + f_1 = \frac{\gamma p_2 k_2}{t_n} + f_2$$

or

$$p_1 k_1 - \gamma p_2 k_2 = t_n (f_2 - f_1)$$

with the left side of the last equation represents the increase in fixed costs and the right side represents the savings in variable costs. The permissible building costs of the projected generation station compared with the replacement generation station are

$$k_{01} = \frac{\gamma p_2 k_2 + t_n (f_2 - f_1)}{p_1}$$

From this we find:

for $\gamma = 1{,}0$ is $k_{01} = \frac{p_2 k_2 + t_n (f_2 - f_1)}{p_1}$

for $\gamma = 0$ is $k_{01} = \frac{t_n (f_2 - f_1)}{p_1}$

In the case of wind generation stations, it can be assumed that the operational expenditures are almost independent of the energy produced. In this case we may set f_1-0 and for $\gamma = 0$ we find

$$k_{01} p_1 = t_n f_2 \quad \text{or} \quad k_{01} = \frac{t_n f_2}{p_1}$$ / 143

If the variable power output of the wind generation stations must be guaranteed completely by other generation stations, then the expenditures for wind generation stations must be met by the fuel savings which is brought about by the wind energy furnished.

In addition, we will evaluate the approximate numerical values of economically feasible building costs for wind generation stations. For simplicity we will assume that variable costs of the thermal generation stations being replaced are only made up of the fuel costs, i.e.,

$$f_2 = \frac{C b}{1000} \qquad (\$/\text{kWh})$$

where b (kg/kWh) the specific fuel consumption,

C ($/t) the fuel cost.

The other operational costs for thermoheat production are included in the fixed yearly costs.

We will assume the following values:

$b = 0.5$ (kg/kWh),
$C = 8$, 12 and 16 (\$/t)
$k = 160$ (\$/kW),
$p_1 = p_2 = 0.10$
$t_n = 2000$(h/year)

The economic limiting values of building costs of wind force conversion plants k_{01}(\$/kW) are given in Table II.

TABLE II. THE ECONOMIC LIMITING VALUES OF THE WIND GENERATION STATION BUILDING COSTS-(\$/kW)

	$\gamma =$	0	0.25	0.50
Fuel cost	$C =$ 8 (\$/t)	80	120	160
	12 (\$/t)	100	140	180
	16 (\$/t)	160	200	240

The table only shows the order of magnitude of the building costs which are justified economically for various roles of the wind generation stations in the total power for joint operation. The coefficient of guaranteed power $\gamma = P_a/P_{an}$ is the fraction of the non-redundant power level, i.e. the savings in thermal energy production which is brought about by each kW of installed wind power generation power. γ is low for small joint systems. In the case of large area joint systems, it can have higher values. If the operation of the wind generation stations can be coordinated in an effective way with the controllable hydroelectric stations, so that the thermal equalization power is reduced, then we could have $\gamma = 0.5$.

The actual building costs of high performance wind generation stations which can be expected are difficult to predict, because no experience has yet been obtained in the building of such wind generation stations. Estimates of required building costs have been made for several large scale wind generation projects [5, 10].

However, because of the widely varying price conditions, these do not represent any bases for determining the expected costs. In addition, prices for the first test installation of wind generation stations cannot give a true picture of the possible building costs of mass produced stations to be built later on. However, based on general considerations we may expect that after several typical types of high performance wind power generation stations have been established and after mass production of these wind stations has commenced, the building costs of the wind generation stations will be maintained within tolerable limits. It should be realized that wind power generation stations offer the possibility of mass production and standardization which is not possible for any other type of power generation station, which will then reduce the building costs.

It can be assumed that in cases where the generated wind power must be completely backed up by thermal power, wind energy will have considerable advantages only for relatively high fuel costs. On the other hand, if wind generation stations are connected to networks of large joint systems, and if there is an appropriate interaction with the hydroelectric stations, they will be able to take on the role of equalization power sources. This will make the increased installation costs of the wind generation stations acceptable. Once the network of individual regions are connected by high voltage overland lines, large joint systems will be produced which will provide favorable conditions for the operation of wind generation stations. Multi-national energy networks over Europe will be especially important for the wind power generation stations, because when they are operated in parallel with hydroelectric stations, such an extensive joint system will be capable of improving the total power as well as the total energy of such an energy supply system. The water reservoirs of the mountain hydroelectric stations will be able to assume the role of energy accumulators for the wind generation stations. This means that differences between demand and supply of energy will be able to be compensated for in an economical manner.

5. CONCLUSION

The supply of energy must be supported by a wide basis of energy sources, and it is necessary to primarily consider inexhaustible energy sources for energy production. At the present time, there is no such high yield energy source which would be capable of meeting the rapidly increasing electrical energy requirement over extended time periods. Therefore, any new energy source does not have to replace the already exploited sources, but should complement them. Favorable conditions for the exploitation of wind energy are produced by the development of joint systems. This is because wind generation stations have a power level which varies widely and it must therefore operate with a large network. The large joint systems can accept energy at any /144 time from the wind generation stations. The power will be equalized by the thermal generation stations for the hydroelectric stations. The joint operation of wind generation stations with reservoir hydroelectric stations has great advantages, because the water reservoirs can be used for equalizing the varying energy offered by all of the dependent generation stations.

Numerous problems are still to be solved in the construction of wind generation stations. There is only a small energy density in the air stream. Therefore, it is necessary to build large diameter wind wheels and these must be installed at sufficient heights. In order to equalize the irregular pattern of the wind flows, it is necessary to have a large number of such stations operating in the network.

In order to investigate the technical questions associated with the wind generation stations, as well as the interaction of the wind generation stations and the overland network, it is first necessary to build test installations and to carry out systematic experiments. Only by collecting sufficient experience will it be possible to exploit wind energy for electrical production in an appropriate way.

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